

Removal of Methyl Orange and Malachite Green from Model Waters Using Pumice Stone as an Adsorbent

D. Martínez-Carbajal¹, Y. Torres-Ortíz¹, D. de la Peña-Aguirre¹, V.J. Cruz-Delgado², C.A. Ávila-Orta², T.E. Flores-Guía¹, D.A. Cabrera-Munguía¹, J.A. Claudio-Rizo¹, G. Alvarado-Tenorio², M.I. Ulloa-Pérez² & L.F. Cano-Salazar^{1*}

¹Facultad de Ciencias Químicas, Universidad Autónoma de Coahuila, Ing. J. Cárdenas Valdez S/N, República, 25280 Saltillo, Coahuila, México. ²Centro de Investigación en Química Aplicada, Enrique Reyna H. 140, San José de los Cerritos, 25294 Saltillo, Coahuila, México.

Corresponding Author (L.F. Cano-Salazar) Email: lucia.cano@uadec.edu.mx*



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ABSTRACT

Water pollution by synthetic dyes represents a pressing global environmental concern due to the persistence and toxicity of these contaminants. In Mexico, the Atoyac River, spanning the states of Puebla and Tlaxcala, has been identified as a severely impacted water body, with high concentrations of dyes primarily discharged by the textile industry. Among the various treatment technologies explored, adsorption has emerged as a highly effective and sustainable method owing to its simplicity, cost-effectiveness, and high removal efficiency. In this study, natural pumice powder, abundantly available in the central region of Mexico, was investigated as an eco-friendly adsorbent for the removal of methyl orange (MO) and malachite green (MG) from model aqueous solutions. The material was used without any chemical modification, achieving adsorption capacities of 4.8 mg/g for MO and 9.2 mg/g for MG with adsorbent doses of 0.1 g and 0.05 g, respectively. The adsorption process was found to be independent of pH, allowing for operation under neutral conditions. Besides, high removal efficiencies were attained with contact times as short as 15 minutes. Kinetic modeling revealed that the adsorption data for both dyes best fit the pseudo-second-order model, indicating a rapid and chemically controlled mechanism. These results demonstrate that using natural pumice powder offers a viable, low-cost, and environmentally sustainable alternative for the remediation of dye-contaminated water bodies such as the Atoyac River.

Keywords: Dyes Pollution; Methyl Orange; Malachite Green; Pumice Stone; Puebla; Tlaxcala; Atoyac River; Textile Industry; Adsorption.

1. Introduction

Water pollution represents a major global concern, primarily because water is an essential resource for the survival of all living organisms and a critical element supporting a wide range of anthropogenic activities. However, these same human-driven activities have led to the widespread release of numerous pollutants into aquatic environments, among which synthetic dyes are of particular concern [1]. Dyes are vital compounds utilized across multiple industries, where they play a key role in imparting color to substrates within the textiles, printing, cosmetics, and food sectors [2,3]. The extensive use and mismanagement of these substances have raised increasing concerns due to their potential environmental persistence and associated toxicological impacts on aquatic ecosystems.

In Mexico, the Atoyac River, spanning the states of Puebla and Tlaxcala, has been identified as a critical site of environmental degradation due to severe dye contamination. The textile industry, heavily concentrated in this region, has been recognized as the principal source responsible for the marked decline in the water quality of the river through the continuous discharge of untreated or poorly treated effluents [4].

This issue is not confined to Mexico but is observed worldwide, necessitating the exploration of techniques for removing dyes from contaminated water. Several methods have been investigated to date, including biological treatments, coagulation-flocculation, electrocoagulation, Electro-Fenton (EF) processes, ozonation, advanced oxidation processes, microfiltration, ultrafiltration, and adsorption, among others [5]. Among these, adsorption is highly favored due to its operational simplicity, cost-effectiveness, and consistently high removal efficiency. The adsorption process involves two main components: the adsorbate, the substance intended for removal, and the

adsorbent, which must be a highly porous material possessing surface functional groups and a high specific surface area. These characteristics enable the adsorbent to attract the analyte through physical and/or chemical interactions. Various materials have been explored for this purpose, including activated carbons, polymers, ceramics, and hybrid or composite materials [6].

Among these alternatives, using naturally occurring and highly available materials has gained considerable attention, offering a cost-effective solution while maintaining high removal efficiencies. One such material is pumice, a highly porous aluminosilicate of volcanic origin [7]. In Mexico, where numerous volcanic regions exist, pumice is abundantly and naturally available, making it an attractive and sustainable option for adsorption applications.

In response to this critical issue—and aligned with the United Nations Sustainable Development Goals (SDGs) outlined in the 2030 Agenda—this study investigates the use of natural pumice powder, sourced from volcanic regions in central Mexico, as an adsorbent for the removal of methyl orange (MO) and malachite green (MG) dyes from aqueous solutions. Furthermore, the adsorption kinetics of both systems were systematically analyzed to evaluate the performance of the material, thus contributing to a better understanding of the underlying mechanisms.

1.1. Study Objectives

The primary research objectives of this study were:

- (i) To investigate various factors that may influence the removal of malachite green and methyl orange dyes using pumice stone powder as an adsorbent, including pH, adsorbent dosage, and contact time.
- (ii) To conduct a comparative analysis of the adsorption capacity of pumice for both dyes.
- (iii) To perform a kinetic study of the adsorption systems by applying the Elovich.
- (iv) To apply pseudo-first-order, pseudo-second-order models to evaluate the adsorption mechanisms.
- (v) To identify the rate-controlling steps involved.

2. Materials and Methods

Pumice stone originates from the central region of Mexico. It was used without any chemical modification and was only ground using a blade mill (CONAIR JC-1016) to reduce its size. Subsequently, the ground material was further processed in an additional mill (BRABENDER) to obtain a fine powder. This powder was then subjected to a sieving process using different mesh screens until the fraction that passed through the 350-mesh screen was obtained. The malachite green (MG) and methyl orange (MO) dyes were obtained from CTR Scientific and Jalmek. To precisely adjust the pH of the dye solutions, sodium hydroxide (NaOH) or hydrochloric acid (HCl) were supplied by Sigma-Aldrich. Deionized water was used throughout the experiments, all conducted in triplicate to ensure reproducibility. To maintain uniform mixing conditions, batch experiments were subjected to continuous agitation using a VWR orbital shaker for the required duration. Subsequently, dye quantification was performed using a Thermo Scientific Multiskan Sky UV-Vis spectrophotometer. The following section provides a detailed description of the methodological procedures implemented in this study.

2.1. Determination of Wavelength (λ) and Quantification of the Dyes

To determine the appropriate wavelength for quantifying dye solutions after adsorption, 50 ppm solutions of each dye (MG and MO) were prepared and scanned in the 300–900 nm range using a UV-Vis microplate spectrophotometer. The data obtained were plotted, and the maximum absorption peak for each analyte was identified. For dye quantification, calibration curves ranging from 0 to 100 ppm were prepared for each dye and measured at their respective λ values. Figure 1 presents the general scheme corresponding to this section of the methodology.

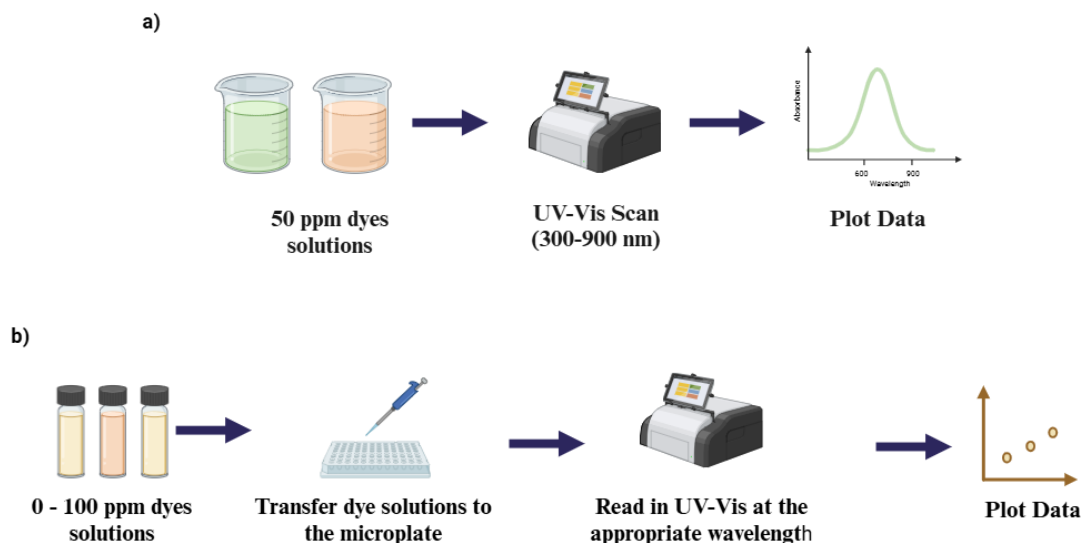


Figure 1. General scheme procedures of a) wavelength determination, b) calibration curve

2.2. Mass dosage effect

For the adsorption of methyl orange (MO), the mass of the pumice stone powder used as an adsorbent varied within the range of 0.10 g to 1.00 g. The initial concentration of MO solutions was selected at 50 ppm (mg/L) to examine the adsorption performance across a broad concentration spectrum. All other experimental conditions, including solution volume, pH, temperature, agitation speed, contact time, filtration procedure, and spectrophotometric quantification, were maintained identical to those established for the MG adsorption experiments to ensure consistency and comparability of the results. The quantification of the dye was performed using a wavelength of 660 nm.

For the adsorption studies involving MG, varying masses of pumice stone powder ranging from 0.05 g to 1.00 g were accurately weighed. The initial dye concentrations were systematically adjusted within 10 to 100 ppm to evaluate adsorption efficiency under different conditions. The experiments were conducted in batch mode using a fixed solution volume of 10 mL, maintaining a neutral pH (~ 7) at room temperature. To ensure homogeneous mixing and maximize adsorption, the system was subjected to continuous stirring at a controlled speed of 220 rpm for a total contact time of 60 minutes. After completion of the stirring period, the samples were subjected to vacuum filtration to separate the solid adsorbent from the treated solution. The remaining dye concentration in the filtrate was subsequently quantified using UV-Vis spectrophotometry at 620 nm. Figure 2 provides a schematic representation of the overall process followed in this methodology section.

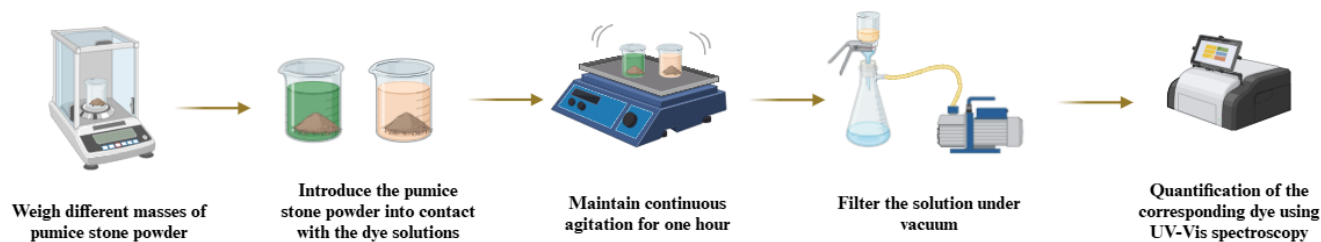


Figure 2. Schematic representation of the general methodology implemented for the mass dosage experiments

Equation 1 describes the method used to estimate the adsorption capacity of the material, expressed in mg/g, providing a quantitative measure of the amount of adsorbate retained per unit mass of adsorbent. Meanwhile, Equation 2 outlines the calculation for the removal efficiency, expressed as a percentage, which allows for the assessment of the effectiveness of the material in eliminating the target contaminant from the solution. These equations are fundamental tools for evaluating the performance and feasibility of the adsorption process under the tested conditions [8].

$$q_e = \frac{V(C_i - C_f)}{m} \quad \text{Eq. 1}$$

$$\%R = \frac{(C_i - C_f)}{C_i} * 100 \quad \text{Eq. 2}$$

Where q_e represents the adsorption capacity of the material, expressed in mg/g, indicating the amount of adsorbate retained per unit mass of the adsorbent. V denotes the volume of the solution used in the procedure, measured in liters, while C_i and C_f correspond to the initial and final concentrations of the analyte, respectively. Lastly, m refers to the mass of the adsorbent used, expressed in grams, which plays a crucial role in determining the efficiency and capacity of the adsorption process.

2.3. pH effect

To determine whether the pH variable influences the adsorption process of MO and MG dyes, solutions of both dyes were prepared at an initial concentration of 50 ppm, and their pH values were adjusted to approximately 4, 7, and 9 using 0.1 M hydrochloric acid or 0.1 M sodium hydroxide. For MO, a solution volume of 10 mL was used with 0.1 g of pumice powder, while for MG, 10 mL of solution was prepared with 0.05 g of pumice. The contact time for both systems was set to 1 hour under constant stirring at room temperature. After the designated period, the samples were filtered and analyzed by UV-Vis spectroscopy at the corresponding maximum absorption wavelength for each dye.

2.4. Contact time effect

Methyl Orange: A mass of 0.1 g of pumice powder was used. Both experimental trials were carried out under strictly controlled conditions at an approximate pH of 7, ensuring consistency and reliability in assessing adsorption performance. Furthermore, the methodology consistently maintained uniform operational parameters, including stirring speed, ambient temperature, and solution volume, to minimize variability and allow for accurate comparison of results. The time range was from 0 – 180 minutes.

Malachite Green: Initial dye concentrations were prepared within 0 to 100 ppm, using a fixed solution volume of 10 mL and a pumice powder mass of 0.05 g. The adsorption process was evaluated over a contact time ranging from 0 to 180 minutes, under continuous stirring to ensure homogeneity, and conducted at room temperature to maintain consistent experimental conditions. Once the predetermined contact times had elapsed, the samples were filtered to remove solid residues, and the resulting solutions were subsequently analyzed through quantitative measurements to assess the extent of adsorption and facilitate further data interpretation.

2.5. Adsorption Kinetics

Adsorption kinetics provide critical insights into the behavior of the adsorbent-adsorbate system, as they can reveal the rate at which sorption and/or desorption processes occur at the solid-liquid interface. This information is essential for understanding the efficiency, capacity, and mechanism of adsorption and optimizing operational parameters in practical applications. Additionally, kinetic studies allow for identifying the dominant mass transfer mechanisms, which can be crucial in predicting the overall performance of the adsorption system [9]. There are various kinetic models to which experimental adsorption kinetics data can be adjusted and analyzed, allowing for a deeper understanding of the system's behavior over time. These models provide valuable insights into the adsorption mechanism, rate-controlling steps, and interaction dynamics between the adsorbate and the adsorbent [10]. This study tested three widely used kinetic models: Elovich, pseudo-first-order, and pseudo-second-order, each offering a distinct perspective on the adsorption process. The theoretical background and mathematical formulations of these models are presented in the following sections.

2.5.1. Elovich model

The model was originally used to describe the adsorption of gases on solid surfaces and was first proposed by Zeldowitsch. [11]. Currently, this model is also used to describe the solid-liquid adsorption process and assumes that the adsorption rate of the adsorbate decreases as the amount retained in the adsorbent increases [12]. Moreover, this model is associated with the description of a chemical process, specifically chemisorption [13]. Equations 3 and 4 describe the nonlinear and linear models of this kinetic model, respectively [14].

$$q_t = \frac{1}{\beta} \ln(1 + \alpha\beta t) \quad \text{Eq. 3}$$

$$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln(t) \quad \text{Eq. 4}$$

Where q_t is the amount of analyte adsorbed at time t (mg/g), α represents the initial adsorption rate of the dye onto the adsorbent (mg/g·min), and β is a parameter related to the surface coverage of the adsorbent and the activation energy (g/mg). Moreover, β is also associated with a decrease in the adsorption rate as the surface coverage of the adsorbent by the analyte increases [15].

2.5.2. Pseudo-First-Order (PFO)

The pseudo-first-order kinetic model, originally proposed by Lagergren, is commonly applied to systems involving solid-liquid phases. This model assumes that the adsorption rate between the adsorbent and the adsorbate is directly

proportional to the number of active sites that remain available on the surface of the adsorbent throughout the process [16]. Equations 5 and 6 present the nonlinear and linear formulations of this kinetic model, respectively.

$$q_t = q_e(1 - e^{-k_1 t}) \quad \text{Eq. 5}$$

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad \text{Eq. 6}$$

Where q_e is the adsorption capacity of the adsorbent at equilibrium (mg/g), q_t is the adsorption capacity of the adsorbent at time t (mg/g), and $k_1 t$ is the rate constant for pseudo-first-order adsorption (1/min).

2.5.3. Pseudo-Second-Order (PSO)

Finally, Equations 7 and 8 present the nonlinear and linear mathematical expressions for the pseudo-second-order model. This kinetic model assumes that the adsorption process is of a chemical nature (chemisorption) and that the adsorption rate decreases as the analyte concentration increases [16].

$$q_t = \frac{t k_2 (q_e)^2}{1 + k_2 q_e t} \quad \text{Eq. 7}$$

$$\frac{t}{q_t} = \left(\frac{1}{k_2 q_e^2} \right) + \left(\frac{1}{q_e} \right) t \quad \text{Eq. 8}$$

Where q_e is the adsorption capacity of the adsorbent at equilibrium (mg/g), q_t is the adsorption capacity of the adsorbent at time t (mg/g), and k_2 is the rate constant for pseudo-second-order adsorption (g/mg·min).

3. Results and Discussion

3.1. Determination of Wavelength (λ) and Quantification of the Dyes

The corresponding absorption spectra were obtained from the 50 ppm solutions of each dye, as shown in Figures 3 and 4 for methyl orange and malachite green, respectively. The maximum absorption wavelengths observed were 660 nm for methyl orange and 620 nm for malachite green, consistent with those reported by the suppliers and literature [17,18].

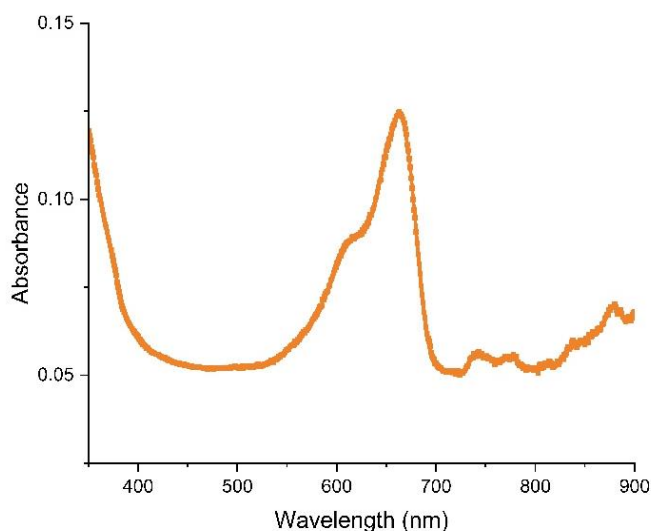


Figure 3. Absorbance Spectrum of Methyl Orange Dye

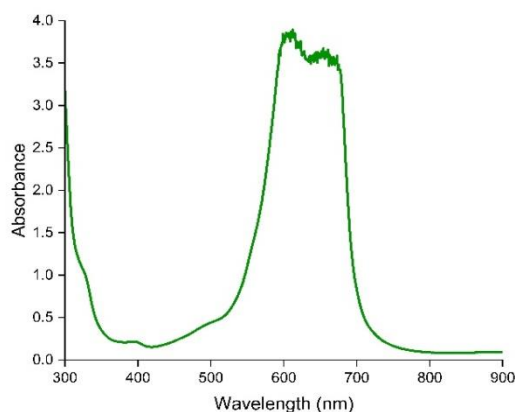


Figure 4. Absorbance Spectrum of Green Malachite Dye

Once the wavelength at which each dye should be measured was determined, calibration curves were constructed to quantify analyte concentrations following the batch adsorption experiments. Figure 5 presents the calibration curves for both dyes, their linear fits, and the corresponding correlation coefficients (R^2).

It is well known that R^2 values close to 1 indicate the reliability of the linear fit for subsequent quantification calculations [19]. In this case, values around 0.98 were obtained for both dyes, confirming that the linear equations can be reliably used to determine concentrations during the adsorption process, ensuring accuracy and precision.

3.2. Mass dosage effect

One of the most critical variables in the adsorption process is the amount of adsorbent used, as the mass is directly associated with the adsorption capacity of the system [20]. Accordingly, a series of experiments were conducted using varying masses of pumice powder for both dyes evaluated in this study.

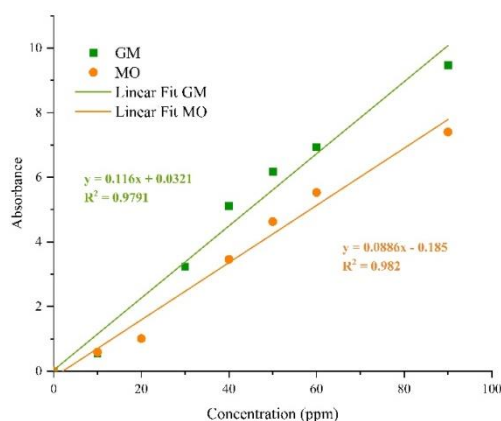


Figure 5. Calibration curves for MO and VM dyes

3.2.1. Methyl orange

Figure 6 presents the adsorption percentages obtained for the various tested masses of pumice powder, calculated using Equation 2. It can be observed that all evaluated masses yielded adsorption percentages of approximately 97%, which corresponds to 48.5 ppm of dye adsorbed onto the surface of the material. Given that the adsorption percentages remain essentially constant across the range of tested pumice powder masses, a mass of 0.1 g (corresponding to a material loading of 10 g/L) was selected for subsequent experiments. Furthermore, the

adsorption capacity of the material for each tested mass was determined using Equation 1; the resulting values are depicted in Figure 7.

Derakhshan *et al.* (2013) reported the adsorption of methylene blue using modified pumice. The modification involved treating the pumice with a 1 N HCl solution to increase the porosity of the material. In their study, a mass of 0.2 g was used in a volume of 50 mL (material loading of 4 g/L). With this material loading and using the same dye concentration as in the present study (albeit using a different dye), adsorption percentages of approximately 90% were achieved, corresponding to an adsorption capacity exceeding 11 mg/g. This value is higher than that obtained in the current work. However, the advantage of the present approach lies in the fact that pumice is a highly abundant material, and therefore, no modification of pumice was performed in this study.

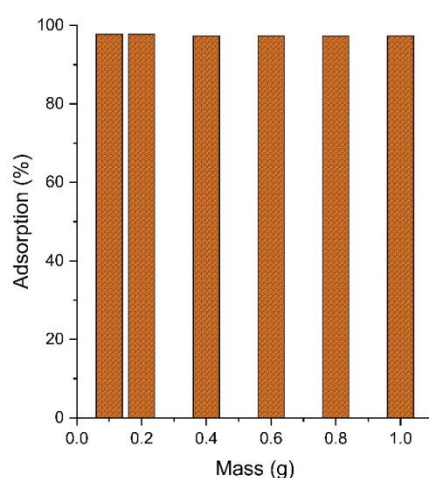


Figure 6. Adsorption percentage of MO using different masses of pumice stone powder

In another study reported in 2023, pumice was modified with SnO_2 via a solvothermal method. The resulting composite was able to remove up to 70% of a solution containing crystal violet and methyl orange through photocatalysis. However, the initial dye concentration used by the authors was only 10 ppm, and the material loading was 32 g/L, which is considerably high [21]. It is important to note that comparisons are made with other dyes and removal methods due to the limited availability of information regarding the adsorption of methyl orange onto pumice.

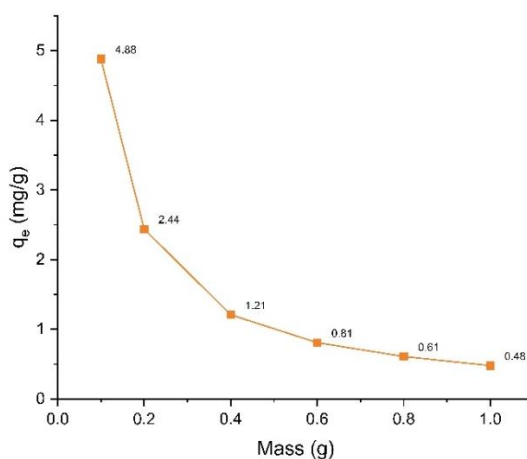


Figure 7. Adsorption capacity of methyl orange for different masses of pumice stone powder

In the aforementioned Figure, the adsorption capacity decreases with increasing pumice powder mass. This result confirms that the lowest tested mass represents the most appropriate working condition.

3.2.2. Malachite Green

In contrast to methyl orange, malachite green was tested using adsorbent masses ranging from 0.05 g to 1 g. For masses equal to or greater than 0.2 g, removal efficiencies between 80% and 90% were achieved for the 50 ppm dye solution. In contrast, for the 100 ppm solution, adsorption percentages exceeded 90% for the same masses. Subsequently, experiments were conducted using lower adsorbent amounts (0.05 g and 0.1 g), and the results showed that pumice exhibited better performance with the 50 ppm solutions, the results are shown in Figure 8. Therefore, the lowest tested mass, corresponding to 5 g/L, was selected for further experiments.

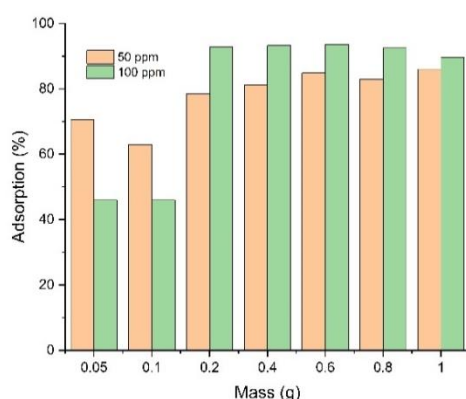


Figure 8. Adsorption capacity of green malachite for different masses of pumice stone powder

Additionally, the adsorption capacity (q_e) was calculated as described in the methodology section. The results of this analysis are presented in Figure 9.

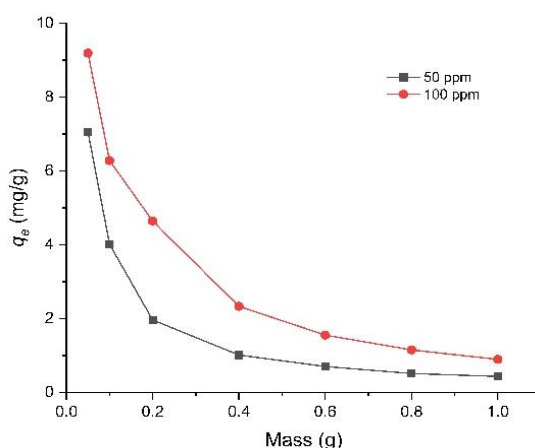


Figure 9. Adsorption capacity of malachite green for different masses of pumice stone powder with 50 and 100 ppm initial dye concentration

This figure shows that the highest adsorption capacity is achieved with the lowest adsorbent mass, 0.05 g. This finding justifies the selection of this material loading for the adsorption experiments involving malachite green.

In contrast to the first dye, several studies have reported using pumice for the adsorption of MG. One such example is the work by Shayesteh *et al.* (2016), in which pumice was used as the adsorbent for MG removal. In their study,

material loadings ranging from 5 to 30 g/L were tested in 50 mL dye solutions with an initial concentration of 100 ppm. They observed that the adsorption percentage increased from 31.6% to 74.8% as the adsorbent dosage was increased. [22]. In the present study, similar results were observed, with the removal percentage increasing as the adsorbent dosage was raised. However, it was also found that the adsorption capacity increased as the adsorbent mass decreased because adsorption sites remained unsaturated during the process, and an excess amount of adsorbent was required for dye sorption. [23,24]. This finding supports the selection of the lowest adsorbent dosage, as it ensures optimal dye removal.

3.3. pH effect

Using the experimental conditions described in the methodology section for both dyes, it was observed that the pH exerted no significant effect on dye removal efficiency. Therefore, a neutral pH of 7 was selected for subsequent experiments to avoid the need for acidic or basic adjustment, as the original dye solutions exhibited pH values close to this neutral range. The results of these tests are presented in Figure 10. Table 1 summarizes the adsorption efficiencies achieved at each evaluated pH level for both dyes, with experiments conducted using an initial concentration of 50 ppm. These data provide insight into the influence of pH on the adsorption process under controlled initial conditions.

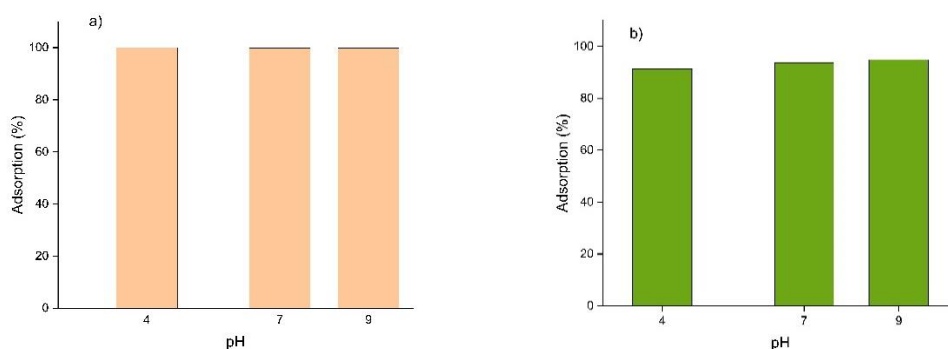


Figure 10. Adsorption percentages of a) MO and b) GM at different pH values

Table 1. Adsorption percentages of both dyes at different pH values

pH	Adsorption (%)	
	MO	GM
4	100.00	91.40
7	99.83	93.79
9	99.81	94.86

A thorough review of the available scientific literature revealed no reports specifically addressing the removal of the dyes investigated herein using pumice stone as the adsorbent material. However, for other dye systems, it has been consistently reported that operating within a pH range of 7 to 8 yields favorable removal efficiencies while also circumventing the need for additional steps such as post-adsorption solution neutralization[25]. In the present work, the adsorption percentages for both dyes exhibited minimal variation across the different pH values tested. Therefore, the natural pH of the dye solutions, approximately 7, was selected for subsequent experiments, aiming to streamline the experimental procedure and ensure conditions conducive to efficient adsorption.

3.4. Contact time effect

In this section, the results pertaining to the removal efficiency of both dyes by pumice stone powder as a function of contact time are discussed. Figure 11a depicts the adsorption behavior for methyl orange, which can be classified as rapid and highly efficient. Adsorption percentages exceeding 90% were attained within the first 15 minutes across all initial concentrations evaluated (20, 40, 60, and 80 ppm), and this performance remained stable throughout the duration of the experiment up to 180 minutes.

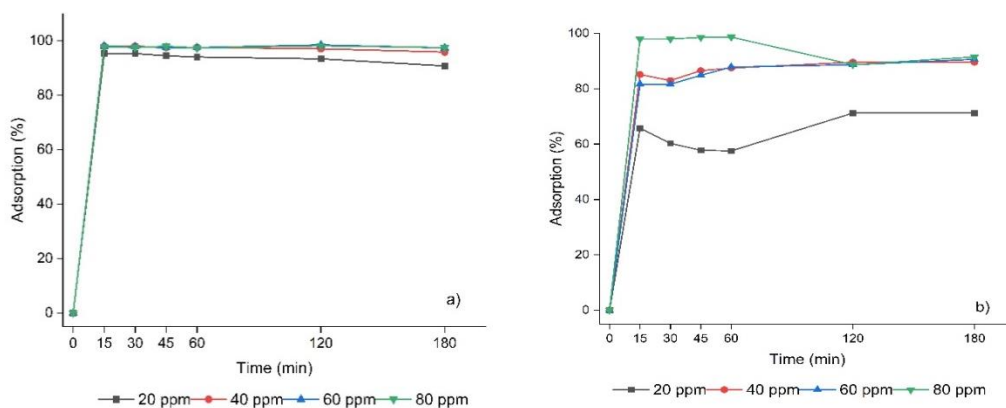


Figure 11. Effect of contact time between the adsorbent at different initial concentrations for dyes:

a) methyl orange and b) malachite green

In contrast, the dynamic adsorption profile of malachite green (Figure 11b) revealed a progressive increase in the adsorbed fraction with increasing initial concentration during the first 15 minutes. Thereafter, a distinct adsorption-desorption oscillation phase was observed from 30 minutes onward. By approximately 120 minutes, the system appeared to approach a pseudo-equilibrium state for all concentrations studied, although minor fluctuations indicated that true thermodynamic equilibrium had not yet been fully established. Nevertheless, considering the high removal percentages achieved from the early stages of contact, it can be inferred that the adsorption process could be effectively conducted at relatively short contact times without significantly compromising removal efficiency.

3.5. Kinetic study

3.5.1. Methyl Orange

To comprehensively evaluate the time-dependent behavior of the system, the experimental data obtained from the kinetic studies were systematically fitted to the different mathematical models described in Section 2.5. The best fit to the experimental data was obtained with the pseudo-second-order (PSO) model, as illustrated in Figure 12. In contrast, the Elovich and pseudo-first-order (PFO) models exhibited lower correlation coefficients ($R^2 < 0.90$). The superior fitting results obtained with the pseudo-second-order (PSO) model further corroborate that the adsorption mechanism is strongly influenced by the relative quantities of both the adsorbate and the adsorbent, underscoring their critical role in determining the overall adsorption performance. Moreover, the PSO model is commonly associated with chemisorption processes, suggesting the involvement of chemical interactions between the functional groups of the adsorbent and the adsorbate molecules [26,27].

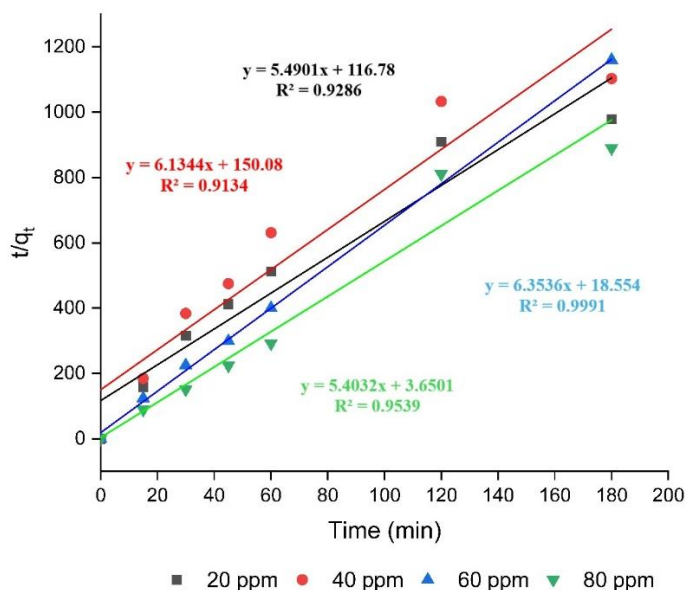


Figure 12. Pseudo-second-order model for the adsorption of MO on pumice stone with different initial concentrations

Furthermore, it was possible to calculate the rate constants (k_2) for the different initial concentrations, yielding values of 0.25, 0.25, 2.17, and 7.99 g/mg·min for 20, 40, 60, and 80 ppm, respectively. This confirms that the adsorption rate is directly related to the amount of adsorbate present in the solution, which is also a characteristic feature of the pseudo-second-order (PSO) model [28].

3.5.2. Malachite Green

The adsorption kinetics of the malachite green–pumice stone system exhibited behavior consistent with that of the previously studied dye, showing the best fit to the pseudo-second-order (PSO) model, with correlation coefficients (R^2) exceeding 0.98 (Figure 13).

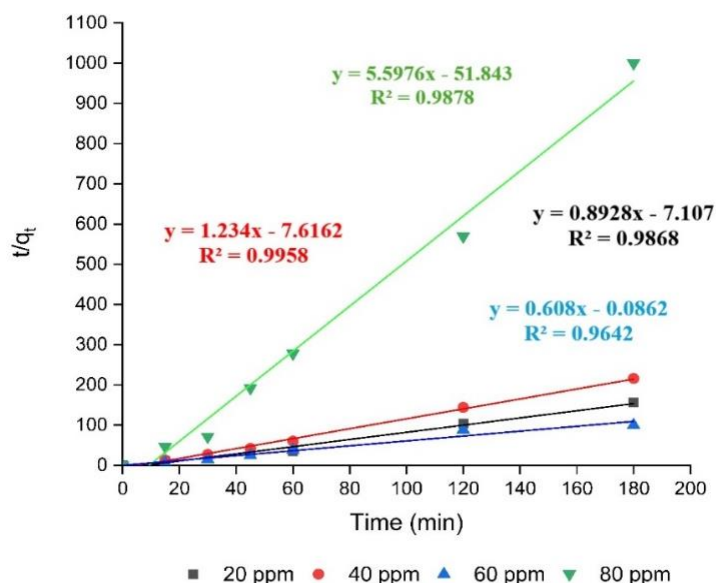


Figure 13. Pseudo-second-order model for the adsorption of MG on pumice stone with different initial concentrations

In contrast, the Elovich and pseudo-first-order (PFO) models yielded R^2 values below 0.90. As observed in the previous case, the good agreement with the PSO model suggests that the adsorption process is of a chemical nature (chemisorption) and that the adsorption rate depends on the amount of adsorbate (malachite green) present in the system. The literature widely reports on the fitting of experimental adsorption data to the pseudo-second-order (PSO) model [29]. For instance, Gürces *et al.* (2023) investigated the adsorption of the cationic dye Remazol Red (RB) onto pumice powder using the pseudo-first-order, pseudo-second-order, and intraparticle diffusion models. Their results showed an excellent fit to the PSO model, with an R^2 value of 1.0, suggesting a strong interaction between the dye molecules and the active sites of the pumice surface [30]. Sawasdee *et al.* investigated the adsorption of Brilliant Green dye onto both natural and acid-modified pumice. Their kinetic data showed the best fit for the PSO model for both raw and modified materials. Based on this, the authors concluded that the adsorption process involves the movement of liquid through the porous material and the adhesion of dye molecules to its surface. Moreover, they observed that the adsorption capacity increased with the initial dye concentration; however, the adsorption rate (k_2) remained essentially constant [31]. This contrasts with the findings of the present study, where, in the case of the raw material, the k_2 value increased with higher initial concentrations of the analyte. In another study reported by Gad *et al.*, irradiated polyvinyl alcohol/starch/pumice composites were used for the removal of Basic Violet 7 dye. Based on experimental kinetic data, the pseudo-second-order (PSO) model was also found to provide the best fit for this system, leading the authors to conclude that the adsorption process is governed by chemisorption [32]. As evidenced by multiple studies using pumice—whether in its raw form, chemically modified, or incorporated into composite materials—the kinetic behavior of adsorption consistently aligns more closely with the PSO model.

4. Conclusions

This study used pumice stone powder to remove MO and MG dyes from model aqueous solutions. The adsorption percentages for both dyes were independent of the adsorbent mass, as consistent removal efficiencies were obtained across the various adsorbent dosages evaluated. However, it was evident that the adsorption capacity increased when lower amounts of pumice powder were used. Consequently, adsorbent masses of 0.1 g for MO and 0.05 g for MG were selected for subsequent experiments. These optimized dosages achieved adsorption capacities of 4.8 mg/g for MO and 9.2 mg/g for MG, respectively. Furthermore, it was demonstrated that the pH of the solution had no significant influence on the adsorption process for either dye. Therefore, a working pH of 7 was established, as it closely matches the natural pH of the dye solutions. Regarding contact time, it was observed that high removal efficiencies for both dyes could be attained as early as 15 minutes. Kinetic studies revealed that the adsorption of both MO and MG followed the pseudo-second-order model more accurately, suggesting that the process is rapid, chemically controlled, and dependent on the analyte concentration. Overall, this work demonstrates the feasibility of using pumice stone powder for the adsorption of these dyes without any chemical modification, thereby offering a sustainable and environmentally friendly approach to dye removal from aqueous systems. Furthermore, the results suggest that this method could serve as a promising alternative for the remediation of dye-contaminated water bodies, such as the Atoyac River in Mexico, where severe pollution from industrial dye discharges has been reported.

Based on the results obtained in this research work, new avenues for investigation are opened, such as:

- 1) Scale-Up and pilot-scale implementation,
- 2) Surface modification to enhance performance,
- 3) Integration into multistage treatment systems, and
- 4) Application to real wastewater and environmental monitoring.

Implementing these future directions is crucial to validate the real-world applicability, enhance the adsorption efficiency, and ensure the environmental safety of pumice-based treatment systems. Such advancements will strengthen its potential as a sustainable solution for dye-contaminated water remediation.

Declarations

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Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

The authors are willing to share the data and material according to relevant needs.

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